KINESTHETIC COMPENSATION FOR MISALIGNMENT OF TELEOPERATOR CONTROLS THROUGH CROSS-MODAL TRANSFER OF MOVEMENT COORDINATES[1]

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When a teleoperation system's remote image sensor is oriented so as to misalign the display coordinates in which the user must operate, control difficulties arise. Users then must learn to compensate for a rotational sensorimotor rearrangement. A new compensation technique is proposed in which the hand not used for control provides a kinesthetic cue to the rotation. In essence, the cueing hand provides a kinesthetic reference for the movement of the controlling hand. Users then make their control movements relative to their kinesthetic sense of the cueing hand's orientation. Experiments show that this technique can reduce control disturbances for some misalignments by up to 64%.

INTRODUCTION

Rotational misalignments are encountered in teleoperation and telerobotics when the remote image sensor, usually a camera, is oriented so as to rotate the resulting display in which users must operate (e.g., Smith & Smith, 1962, chapt. 9-10; Bernotat, 1970). Users accordingly compensate for this misalignment through practice, camera adjustment, or multiple camera images. The impact of and adaptation to various sorts of such misalignments have been studied since Smith & Smiths' book (1962) by Ellis, Tyler, Kim & Stark (1992), Cunningham & Vardi (1990), Smith, Henning, & Li (1998), and Krakauer, Pine, Ghlardi & Gehz (2000).

The adaptation required to deal with control misalignments encountered in teleoperation is related to that for sensorimotor rearrangements produced by optical distortions. However, the misalignments we consider below are distinct since they are exocentrically rather than egocentrically referenced. Furthermore, since the users' displays and controls are often physically displaced from each other, the users experience a sensory motor distortion with respect to an abstract object rather than a part of their body as with customary optical distortions. This latter distinction clearly affects the way users adapt to the misalignment: Clower and Boussaoud (2000) have shown that sensory motor adaptation is markedly attenuated when the visual error feedback resulting from the distortion is not associated with a visible body part.

Users of teleoperation systems can learn, however, to adapt to work with misaligned control axes though visual motor skill acquisition. But multiple rotations can be challenging and are usually avoided by appropriate camera placement. Additionally, if the remote camera can be instrumented and the control is mediated by a computer, the misalignment can be computationally corrected as done for the robot arm on the Space Shuttle Orbiter.

This type of rotational correction of resolved robot arm control is a form of partial automation. As in other forms of automation, there remains a need for manual back up. In fact, an instance of such a need occurred during the deployment of the Hubble Space Telescope when Astronaut Hawley (1995) switched to a less processed form of arm control because the resolved mode appeared to be malfunctioning. Thus, because of the continuing need for manual back up and the fact that the sensing of camera position may not always be possible, interest continues in behavioral techniques to manage rotated control frames.

A new compensation technique is reported below in which the hand not used for control is utilized to provide a kinesthetic cue to the camera orientation, thereby greatly reducing the difficulty in compensating for the control-display misalignment. In essence the cueing hand, which is positioned to copy the attitude of the viewing camera, provides a kinesthetic reference for the movement of the controlling hand. Users then make their control movements relative to their kinesthetic sense of the orientation of the cueing hand. This technique is related to Guiard's (1987) idea that the left and right hand working together may be represented by a closed kinematic chain in which the nondominant hand forms the frame of reference for operation of the dominant hand. In addition to demonstrating the new phenomenon of kinesthetic cueing during manual control, the experiment below tests Guiard's implicit suggestion that the left hand could provide a better kinesthetic cue for the right than the right does for the left.

METHODS

Subjects

24 strongly right-handed subjects (20-35 yrs) were assigned to 4 groups of 6, matched across groups for age, gender, and technical background. Engineers or physical scientists were considered technical, others nontechnical. Group makeup: 1 technical woman, 1 technical man, 1 nontechnical woman, and 3 nontechnical men. Subjects were selected from laboratory assistants or from a NASA subject pool. Their handedness was determined by the Edinburgh Handedness Inventory. All were naïve to the purposes of the experiment and paid for participation.

Equipment

A customized C++ program was written for a Micron laptop PC (Pentium 166) with a 27.1 X 20.5 cm XGA LCD screen running Windows 95. The computer was interfaced through a serial port to a 9.6 x 12.7 cm Wacom (4X5 model) graphics tablet. Stylus position

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data were collected at 100 Hz. Only a circular central region (9 cm diameter) of the tablet was used in the experiment. The remainder was masked off with heavy black cardboard.

Using the stylus, the subjects moved a cursor, shown as a circle with inscribed cross, from an initial position at the screen center to touch a variably sized and positioned circular target. Initial contact with the center of the tablet triggered movement recording. Subjects were not permitted to see their hand moving the stylus when viewing the moving cursor (Figure 1-left).

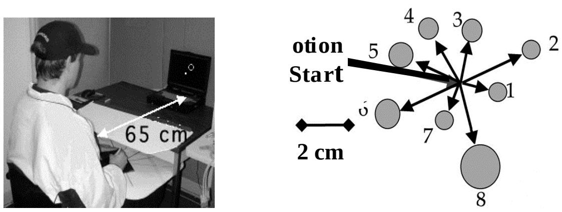

Figure 1. Subject performing the experiment (left). Schematic example of a block of 8 experimental targets(right).

The target was randomly located at one of 8 approximately equally spaced directions to make a block of movements. Randomization of direction (range = ±4°) and amplitude of movement (±0.9 cm) kept subjects unsure of the size and direction of any movement. Thus, stereotyped movement patterns were prevented. The variation was identical for each matched set of subjects, but differed across sets, precluding analysis of target direction as an experimental variable.

The cursor had a diameter of 0.5 cm while the target diameter varied between 0.3 and 0.6 cm. Target size was changed to keep a constant Fitts index of difficulty of 2.6. Movement amplitude varied between 1.8 and 3.6 cm (See Figure 1-right). The visual frame of reference for the experiment was evident from the display frame. All display elements were drawn in single pixel width at ~16 cd/m^2 and were viewed from 65 cm.

Experimental Design

The following experimental conditions presented to the four separate groups of 6 subjects: *No Cue, Kinesthetic Cue, Cognitive Control,* and *Postural Control* (Figure 2).

In the *No Cue* condition, the control frame of reference was rotated in a constrained random sequence to either 0°, ±30°, or ±60° rotation (cw > 0) with respect to the visual frame of reference. Subjects were unaware of the direction and magnitude of the rotation except from the visual feedback during their motion of the cursor. The same rotation was maintained for each block of 8 movements. After each block, the rotation was randomly changed. The same rotation was not presented for more than two blocks in a row. After the cursor touched the target circle, it disappeared and reappeared at the center of the display, waiting for the subject to initiate the next movement by placing the stylus at the center of the graphics pad and moving towards the next target. The set of 5 differing rotation conditions were repeated three times for a total of 15 randomly presented blocks of 8 movements— i.e., each subject made a total of 120 separate movements for a session. Sessions were repeated in counterbalanced order for testing of subjects' dominant and nondominant hands.

In the *Kinesthetic Cue* condition, otherwise similar to the No Cue condition, the subjects actively rotated their cueing hand (the one not moving the cursor). This rotation was made to physical markers on the control surface; these markers were identified haptically, with the experimenter's assistance if necessary. The subjects' view of their cueing and moving hands was obscured during the rotation procedure as well as during the actual experiment. Before beginning the experiment the use of their sense of hand direction to aid control in the rotated coordinate system was explained to all subjects. In particular, they were told to think of their hand movements as relative to the long axis of their cueing hand which was to be thought of as representing the straight ahead on the display.

The *Cognitive Cue* condition was identical to the kinesthetically cued one except that instead of a hand position, the experimenter told the subjects how the control coordinates had been rotated. Subjects were explained and shown with experimenter's hand movements that because of the rotation, a cursor movement straight ahead on the display would now require an oblique movement with respect to their torso. As in the uncued case, the subjects were told to keep the noncontrolling hand on their lap.

The Postural Control condition was similar to the Cognitive Cue but used a postural cue to differentiate the separate blocks. In the this condition, each block of movements made with a fixed rotation was distinguished from the others by having the subjects change the posture of their hand not controlling the cursor. They were instructed to hold it in one of five different poses (Figure 2). The assignment of postures was random for each subject, but identification of symmetrical rotations, e.g. +45° and –45°, with symmetrical hand postures was avoided.

Seidler, Bloomberg, and Stelmach (2001) suggest that postural cues could be used to help segregate simultaneous sensorimotor adaptation. Hence, this condition was intended to examine whether nonspecific postural cues themselves might aid the subjects' ability to separate the blocks presenting different rotations. The cognitive cue and postural control conditions were introduced to check whether the kinesthetic cue helped not by providing kinesthetic orientation information, but by simply informing the subjects that the transformation conditions had changed. They would not have this information in the No Cue condition, but would in all the cued conditions. We hypothesized that the kinesthetic cue would provide the strongest differentiation cue. In a sense the kinesthetic cue condition combines the specific quantitative rotation information provided in the cognitive cue with the kinesthetic marking of different rotation conditions signaled by the different hand postures.

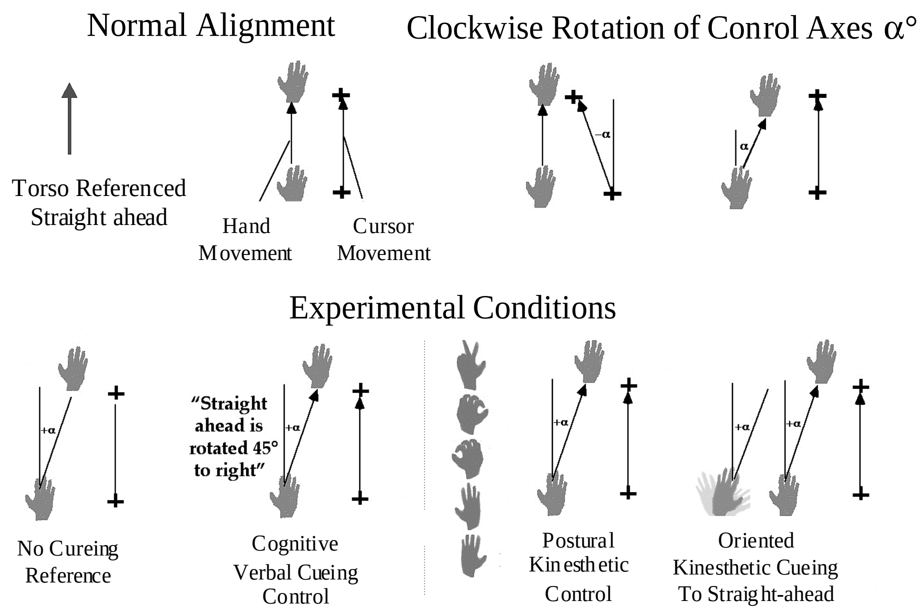

Figure 2. Cursor movement under aligned and rotated coordinates.

All conditions were preceded by a warm-up period during which subjects were requested to make 5 blocks of 8 movements without a rotation. During these movements, subjects were told to develop a movement rhythm that they could continue thereafter when the movements would become harder. In this way, each subject was able to find a comfortable speed/accuracy trade-off for the experiment. We used the average path lengths to each of the targets during the warm-up to normalize each subject's response path lengths for each target. About 10% of the subjects' movement records had discontinuities caused by lifting the stylus off the graphics pad. These records were removed from the analysis by a special filter.

Normalized path length was computed for all movements and used in a mixed-design ANOVA for Cue condition (4 levels), Hand-in-Control (2 levels), and Order-of-Hand-Use (2 levels). Subjects were nested within Order-of-Hand-Use and crossed with Cue and Hand-in-Control, i.e., Cue X Hand X Order(Subjects)

RESULTS

Figure 3 presents sample individual movements from two matched subjects who were presented with identical sets of movement targets. The effect of the rotational misalignment is visually evident in the longer, arced trajectories for the rotated condition. This effect is, however, attenuated in the kinesthetic cue case.

Figures 4-7 include only the statistically significant results from the ANOVA of normalized path length. Because of inhomogeneity of variance, log transforms were applied to the data to verify statistically significant effects. Reported statistics are based on the untransformed data since the statistical conclusions were unaffected by the transformation.

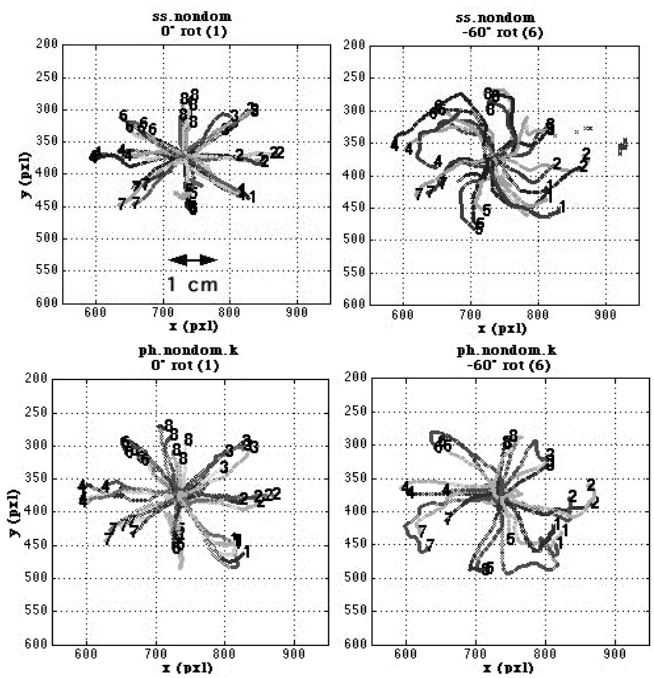

Figure 3. Individual movements from a pair of matched subjects for unrotated (0°) and a -60° rotated conditions. The upper pair of plots is from a subject in the No Cue condition and the lower pair from one in the Kinesthetic Cue condition. Numbers represent order of movement used for this pair of subjects.

As shown in Figure 4, only the kinesthetic cue significantly reduced the normalized path length of the movements. This effect was strongest for the larger control frame rotations (Figure 6) and there was no suggestion of either a main effect or interaction with the hand used to move the cursor (Figure 5). Had there been a hand effect according to Guiard, the moving right hand should have benefited more from left hand cueing rather than visa versa.

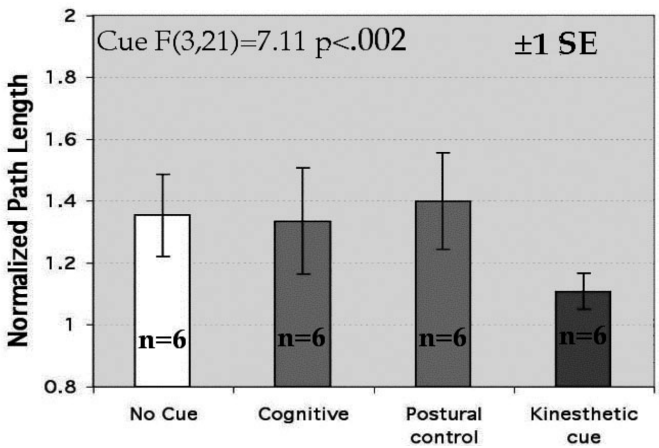

Figure 4. Main effect of cueing type.

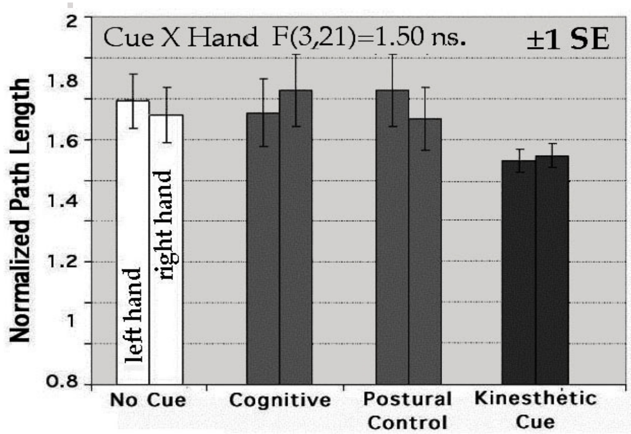

Figure 5. Interaction between the hand controlling the cursor and the type of cueing.

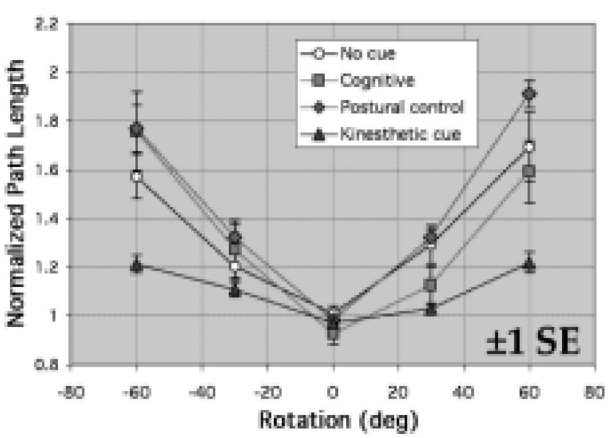

Figure 6. Interaction between rotation direction and cueing.

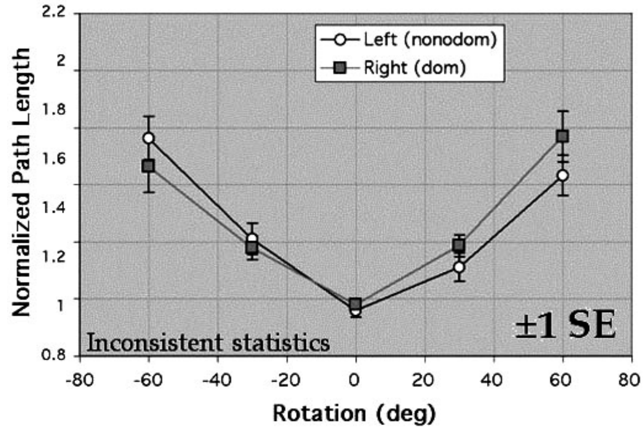

Figure 7. Interaction of hand of use and rotation

DISCUSSION

The results show that kinesthetic cueing can improve control by up to 64% and could be the basis of development of a kinesthetic "prop" to aid interaction (Hinkley et al., 1997). The current experiment, however, does not indicate whether the improvement can occur without explicit subject instruction.

Interestingly, the cueing effect appears to be symmetrical, with dominant and nondominant hands being equally effective as cues (Figures 5 and 6) (cf. Guiard, 1987). Possibly, the precision required for the movement was insufficient to show a difference and a higher Fitts Index of Difficulty should be tried. Furthermore, the between subjects design might not have been statistically powerful enough to show a hand-of –use effect.

Alternatively, the expected laterality effect might show up with a different dependent measure such as movement time. We have examined this possibility but have not found any effects of hand use on movement time or speed that could be interpreted in terms of the nondominant hand providing a better frame of reference information for the dominant hand. In general, our analyses of temporal effects have been predictable from our analyses of normalized path length and the fact that our subjects on average tended to move at a constant speed, as they were instructed to during the warm-up session.

A "virtual force" model suggested by Cunningham and Vardi (1990) has been fitted to some of the mean movement data from a subsequent pilot experiment. It may provide a parametric technique to model the improvement of movement efficiency made possible by the kinesthetic cue. This model assumes that the subject is repetitively attempting to make incremental movements toward some point on the target circle and that these movements are disturbed by a "virtual force." This force is thought to act on each increment to rotate its vector away from the correct target direction (Figure 8). As shown by Figure 9, this model can be readily fit to averaged path trajectories. It cannot, however, capture the frequent discontinuities in individual path trajectories. Individual movement fits will probably require incorporation of the predictive aspect of sample data hand movement models (e.g., Navas & Stark, 1968).

Figure 7 shows a hint of an interaction previously reported by Liao and Johnson (2001) suggesting a hand bias during hand movement under rotational distortion. This apparent interaction occurs across all cues and therefore must be related to the underlying hand movement kinematics. Though the interaction is not significant when using normalized path length as a dependent variable. ($F(4,80)=0.678$, ns), it is significant when speed is analyzed ($F(4,80)=2.872$, $p < .028$) We have recently conducted a statistically more powerful experiment than the present one and can confirms that this interaction is real.

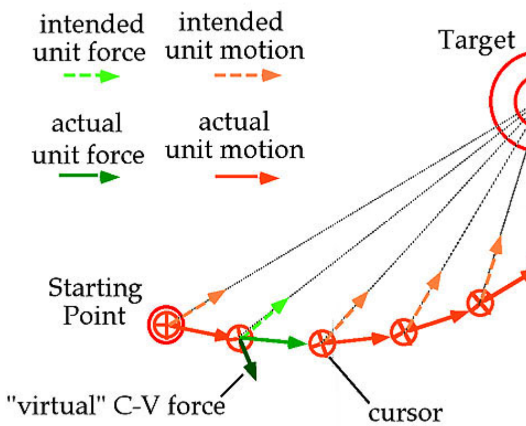

Figure 8. Illustration of the virtual force model.

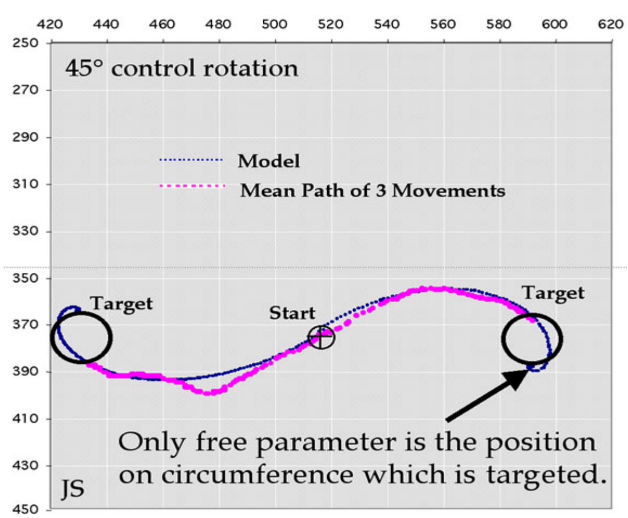

Figure 9. Least-squares fit of virtual force model to averaged trajectories from a single subject's movement to two different targets.

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